Procedia Computer Science
Volume 88, 2016, Pages 365–370
7th Annual International Conference on Biologically Inspired Cognitive Architectures, BICA 2016

Modeling of Antenna System for Capsule Endoscopic Complex "Landish"

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Abstract
This article focuses on modeling of different options of antenna system including and in particular an antenna for the capsule endoscope (transmitter antenna) of the capsule endoscopic complex "Landish". A helical antenna is reviewed for the transmitter, as well as a patch antenna on a curved substrate, and a quarter-wave monopole vibrator and a ceramic antenna. An experiment was conducted in order to compare the gain of the antennas at a fixed position in the space of the transmitting antennas, and the impact of the human body on the features of antennas. Recommendations on the choice of antenna systems in accordance with the simulation results are provided.

Keywords: Antenna system for endoscopic complex, antenna for a transmitter, patch antenna, helical antenna, quarter-wave monopole vibrator

1 Introduction

Wireless capsule endoscopy is becoming increasingly popular as a means of primary screening diagnosis of human gastrointestinal (GI) tract. A wireless endoscopic capsule allows to conduct a survey of all the digestive tract, to identify zones with pathologies and/or morphological changes in organs, and to diagnose and treat the patient timely without causing any discomfort to the patient and without constraining the patient's daily lifestyle (Kukushkin 2012, Mikhaylov 2014a). Recent advances in this area allow the capsule to stop at the desired location of the digestive tract for a more detailed examination in real-time (Mikhaylov 2015a).

Recent developments in the capsule endoscopy emphasized the need for precise methods for estimating the location of the endoscopic capsule in the digestive tract of the patient. For example, Ara et al. (2014) present comparison of half-dipole and loop at the frequency of 2.4 GHz to explore and compare the effect of different antenna types. Kyeol Kwon et al. (2012) propose an antenna for use in

Selection and peer-review under responsibility of the Scientific Programme Committee of BICA 2016

doi:10.1016/j.procs.2016.07.450

a capsule endoscope system. In (Mikhaylov 2014b), the authors discuss the development of the planar antenna for the reader of capsule endoscopic complex, which would meet the requirements of the system for the operation duration, be of a miniature size and has high sensitivity. Lee et al. developed a broadband helical antenna for endoscopic capsule; their article presents the results of its testing on pigs (2011). Finally, the article by Mikhaylov et al. (2015b) focuses on the development of specialized antennas for a 2.4 GHz reader; the antenna must be powerful and has low power consumption to ensure the functioning of the reader throughout the full examination procedure of the gastrointestinal tract of the patient.

Manufacturers of capsule endoscopic systems develop their own antennas for readers or use the existing element base. Existing solutions have their advantages and disadvantages (Mikhaylov 2013). The latter include high resolution and considerable power consumption. Therefore, it was decided to develop customized transmitter antenna for the capsule endoscopic complex "Landish". Such an antenna would provide continuous operation of the complex for at least eight hours; have high sensitivity. The results obtained in previous studies of the research group and described in (Mikhaylov 2014b, Mikhaylov 2015b) were used for the development as well.

Transmitting antenna for capsule endoscopic complex will be calculated for 2.5 GHz frequency, as the transceiver with the coordination chain, proposed for use, has maximum sensitivity at that frequency. In addition, according to the article describing the frequency range for such endoscopic system (Kahn 2010), the loss in the human body decreases when approaching the 2.5 GHz compared to the frequency of 2.4 GHz. These factors presumably will increase the signal/noise ratio for dB units (about 4-5 dB), which under the current theoretical calculations is not enough to achieve the bit error rate of 10^{-5}.

2 Modeling Capsule Antenna

The design of the transmitter antenna should be guided by the following criteria:

- minimal dimensions allowing the antenna to fit inside the capsule endoscope;
- the antenna must have linear polarization;
- the antenna must be matched to 50 Ohms;
- the antenna pattern must be chosen based on the location of the endoscopic capsule inside the human body.

All the embodiments of the simulated antennas have been considered in the singe environment – airspace model – and in the double environment – airspace simulating the air inside the capsule and the outside casing imitating a human body averaged parameters (dielectric constant, dielectric loss tangent, conductivity). It is agreed in advance that the “real” experiments conducted on fabricated antennas are different from models in double environment.

When choosing the type of antennas for the transmitter several options were considered: a helical antenna, a patch antenna on a curved substrate, quarter-monopole vibrator and a commercially available ceramic antenna. Let us consider each of the options in more detail.

Helical antenna

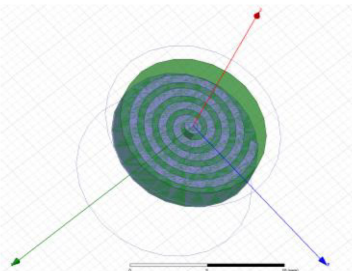
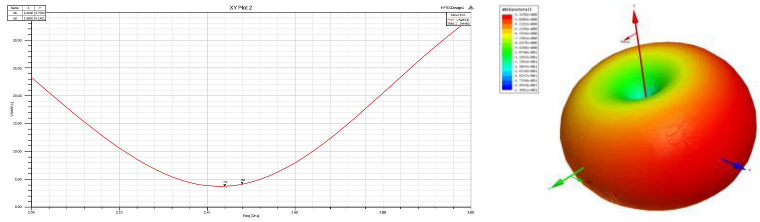


Figure 1: Model of a helical antenna

The helical antenna is a traveling wave-band antenna, the main element of which is the conductor in the form of a helix or spiral. A specific feature of helical antennas is their high input impedance, allowing in some cases to bring it to 50 Ohm for transmission over conventional coaxial cable without the use of matching transformers (Kraus 2002).

The model of the helical antenna is shown in Figure 1, and its features are listed in Figures 2a (SWS) and 2b (gain).



a b

Figure 2: (a) SWR of the helical antenna model and (b) the gain pattern of the helical antenna model.

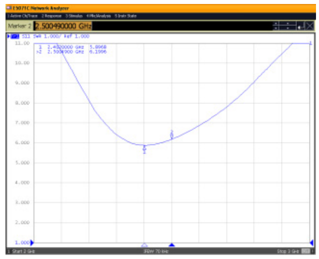


Figure 3: SWR of the helical antenna model.

It is worth noting that the helical antenna is taken from articles on foreign analogical systems for capsule endoscopy (Lee 2011, Kwak 2005, Lee 2008, Lee 2010), but operating at frequencies close to 430 MHz. The figures above show that the attempt to “transfer” this antenna to frequencies close to 2.5 GHz did not show any outstanding results. SWR of the antenna is not lower than 3.7 and the gain does not exceed 1.9 dB.

Despite the disappointing results of the simulation, it was decided to produce such an antenna. The layout of the helical antenna is shown in Figure 3. SWR of the helical antenna model is shown in 7b. The resulting SWR is poor. An experiment to measure the coefficient of transmission between the helical antenna model and the described patch antenna for the receiver also showed unsatisfactory results.

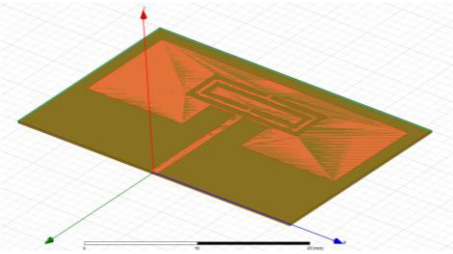


Figure 4: Model of the patch antenna on a curved substrate.

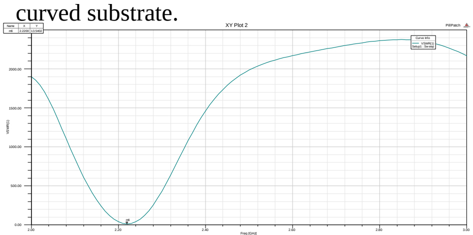


Figure 5: SWR of the model of the patch antenna on a curved substrate.

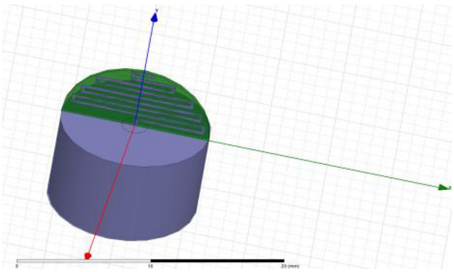


Figure 6: Model of the quarter monopole vibrator.

Patch antenna on a curved substrate

One possible embodiment of the antenna was designed specifically for endoscopic capsule and patented by Chinese developers. It is a patch antenna for 9.16 GHz, with a resonator drawn on it, “transporting” the operating frequency for 2.4 GHz (Cheng 2011). The position of the resonator (cutouts) adjusts the frequency at which the antenna will work. Dimensions of the matching element (rectangular cutouts to the left and the right of the feed line) allow to adjust the SWR. A plain model of this antenna is shown in Figure 4.

Simulation of parameters of the antenna did not give positive results, in particular, it could not achieve acceptable performance at 2.5 GHz. SWR is shown in Figure 5.

Thus, it is necessary to recognize the failure of the implementation of the said antenna at this stage.

It is worth noting that in the case of successful realization of the design of this type of antenna will have some retreat from the concept, allowing to place a plane with a land polygon on one side of the battery charge.

Quarter wave monopole vibrator

Another embodiment of antenna for use in a capsule endoscope is quarter wave monopole vibrator. It is a monopole line vibrator whose length is equal to a quarter of the wavelength (Zhao 2010). An antenna of half-wave monopole vibrator type of one of commercial capsule endoscopes, clocked at 2.4 GHz. The antenna pattern of this kind is a torus, perpendicular to the plane of the circuit board.

Thus, it appears that an antenna arranged parallel to the transmitter board, will have a "torn" chart.

Given the above data and the concept providing the presence of the ground polygon for the battery connection, the design of a quarter-monopole vibrator was modeled and shown in Figure 6.

The mentioned model has the features shown in Figures 7a (SWS) and 7b (gain).

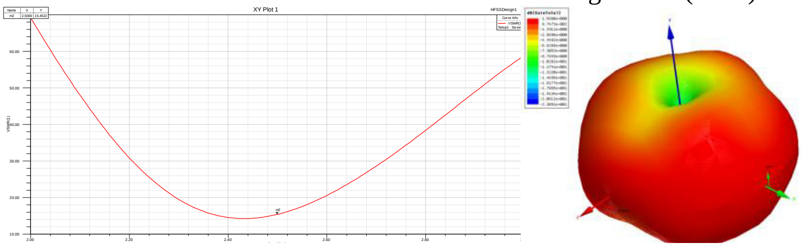


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Figure 7: (a) SWR of the vibrator model and (b) gain of the vibrator model

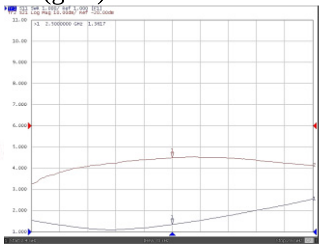

Figure 8: SWR of the monopole vibrator layout

From Figure 7a it is clear that at the desired frequency of 2.5 GHz the SWR is large. Therefore, a matching circuit was provided for the antenna prototype.

Figure 7b shows that, in contrast to the helical antenna, the gain is up to 1.56 dB. In addition, it can be seen that the vertical antenna installation method avoids nulling in the pattern diagram.

It should be noted that the modeling of antenna was also conducted without batteries. In this case, it turned out that directional pattern has gaps.

Figure 8 clearly shows that the antenna has good SWR performance in a fairly wide band of frequencies. To adjust the SWR only one standard size of inductor 0603 was used. It should be noted that, just by changing the denomination of the inductor, the antenna can be tuned over a wide frequency range.

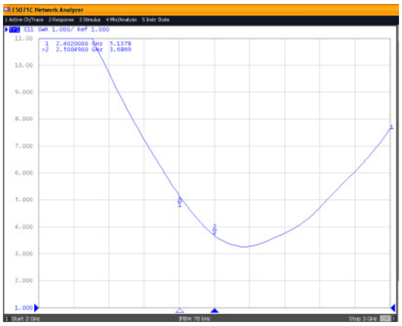

Figure 9: The layout of VSWR 2450AT42A100E antenna

The antenna design may be questionable in terms of the assembling in series production, but, in our opinion, this issue can be solved by the following construction.

Commercially available serial ceramic antenna

2450AT42A100E was used as a ceramic antenna. Topology recommended by the manufacturer was used to simplify assembling, but it was implemented by space-wired interconnections.

The minimum SWR, shown in Figure 9, is shifted in frequency because of the thin dielectric layer, but even in this case, it is seen that it does not show good performance. In addition to the below average SWR, this antenna has a structural defect – the height of the antenna with the reference topology is 9 mm, which exceeds the radius of the hemisphere dome of the capsule (inner radius of 5.75 mm). This shortcoming does not allow to use this antenna without prejudice to the overall design of the capsule.

3 Results and Conclusion

All antennas modeled for the experiments were set approximately at the same frequency. Unfortunately, it was not possible to check the antennas in an anechoic chamber, so all the experiments were carried out on the table. The purpose of the experiments was to compare the gain of the transmission antennas at a fixed position in the space, as well as the influence of the human body on the antenna features.

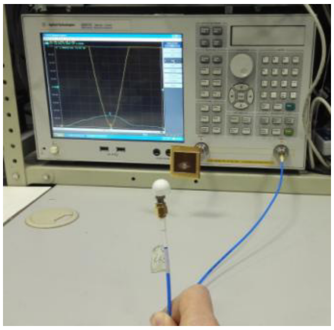

Figure 10: Scheme of the experiment

In the experiment, the generator delivers a signal to the antenna (the signal is a sine wave with a variable frequency), the receiving antenna is connected to a spectrum analyzer, which shows the signal (see Figure 10). The signal strength was estimated – the height of the wave's “ridge” which is visible in the spectrum (spectrum is a representation of the signal amplitude as a function of frequency).

The conducted experiments showed that with the other parameters being equal, the antenna gain were distributed to the following positions in the degree of reduction:

1. the quarter-wave monopole vibrator;
2. the half-wave monopole vibrator;
3. ceramic antenna 2450AT42A100E;
4. helix antenna.

It should be noted that the difference between adjacent positions is approximately 3-5 dB.

In our view, the losing position of the half-wave monopole vibrator is due to its constructive position (horizontally above the underlying surface), which adversely affects the antenna pattern.

An experiment was conducted with the vibrator aimed at testing the effect of the human body on it. For the experiment, the antenna was placed in the mouth under the tongue, and the experiment was repeated. We analyzed the transmission coefficient and SWR – it was important to understand how the crest was “moving” on the horizontal axis (i.e., the frequency axis) of the proximity to the body tissues. In this case, placed in the mouth at a fixed position in the space, the antenna transfer coefficient decreased by 10 dB.

The degree of influence on the human body on the SWR was big enough. The shift of the minimum occurred roughly at 250 MHz. This influence can be controlled by a shift upwards in the operating frequency of the antenna. The only obstacle in this case is the difficulty of the experiment.

Thus, according to the results of the simulations of different options for the endoscopic capsule antenna the following conclusions were made:

1. a quarter-wave monopole vibrator showed the best features when selecting the antenna for the transmitter;
2. the quarter-wave monopole vibrator can be easily rearranged to achieve the desired frequency response;
3. results of the simulation using space that simulates the human body, showed improved antenna features (SWR becomes better).

It is advisable to choose a quarter-wave monopole vibrator antenna for the capsule for the developed endoscopic system, because it has the best performance and can be easily adjusted.

It is planned to carry out the selected antenna prototyping and testing, as well as rework, increasing the efficiency and enhancing the performance. It is expected that the specification of the antenna will surpass existing analogues by stable uniformly strong signal and minor power consumption for transmission/reception of image and control commands from the capsule to the reader and vice versa.

4 Acknowledgement

This publication was prepared based on the results of scientific research project performed by The NRNU MEPhI and JSC RTI as part of the agreement №02.G25.31.0018 on February 12, 2013 between the Joint Stock Company "Radio Engineering Institute named after Academician AL Mints" and the Ministry of Education and Science of the Russian Federation.

This work was supported by Competitiveness Growth Program of the Federal Autonomous Educational Institution of Higher Professional Education National Research Nuclear University MEPhI (Moscow Engineering Physics Institute).

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